Plasmon-assisted Phase Transition of VO$_2$

Wakana KUBO$^1$, Takuo TANAKA$^2$

$^1$Tokyo University of Agriculture and Technology, $^2$Metamaterials Laboratory, RIKEN
E-mail:w-kubo@cc.tuat.ac.jp

Vanadium dioxide (VO$_2$) exhibits a thermally driven metal-to-insulator phase transition, which accompany drastic changes in resistivity and opacity between metal and insulator phases. In addition to a noticeable transmission change in IR region, VO$_2$ phase transition induces a sharp divergent bulk permittivity around the phase transition temperature, leading to the interest in the research on VO$_2$ surfed with the emergence of plasmonics and metamaterials.

Here we investigate the interaction between plasmons and VO$_2$, that is, in-situ and reversible tuning in material properties of VO$_2$ by plasmons. It is commonly believed that the phase transition temperature of a material is an intrinsic property determined by its chemical composition and the crystal structure. Based on this argument, the most straightforward method to alter the phase transition temperature is to introduce dopant into the material. However, such change is neither in-situ controllable nor reversible, as the phase transition temperature is dictated by the crystal status controlled by doping. In work, we observed plasmon-assisted phase transition by embedding gold nanorods (NRs) into VO$_2$ and realized different transition temperatures by changing Au NRs densities.

Au NR arrays were fabricated by electron beam lithography and Au deposition. Au NR arrays were completely covered with a metal vanadium film, followed by annealing at 440 °C, resulting in a VO$_2$ film embedding Au NR arrays. (VO$_2$-Au NRs)

Transmission spectra with various temperatures were measured under polarized IR light. And the phase transition temperature ($T_{\text{phase}}$) of VO$_2$-Au NRs was calculated from a hysteresis curve obtained from measured transmission spectra. In this experimental setup, only long-axis polarization of Au NR can excite localized surface plasmon resonance (LSPR) since the incident light involves only IR light and the short-axis LSPR of the Au NRs lies in the visible light region. That means plasmon excitation and non-excitation can be switched just by changing polarization directions, leading to the elucidation of the LSPR contribution on VO$_2$ phase transition.

As a result, $T_{\text{phase}}$ of VO$_2$ which does not include Au NRs was (49.0 ± 0.0) °C (n=3) under both polarizations. The $T_{\text{phase}}$ of Au-NRs under long-axis polarization, with LSPR excitation, was (45.7 ± 0.1) °C (n=3), while $T_{\text{phase}}$ under short-axis polarization with non-LSPR excitation was (49.0 ± 0.0) °C (n=3), resulting in the differential $T_{\text{phase}}$ of 3.3 °C. Since these $T_{\text{phase}}$ were measured at the same sample location, and only polarization directions were changed, we concluded that LSPR of Au NRs assisted VO$_2$ phase transition.

In addition, the density dependence of Au NRs on VO$_2$ phase transition was examined. The density of Au NRs was controlled from 0 to 17% by tuning pitches between Au NRs. The density of Au NRs of 0% indicates a bare VO$_2$ film does not include Au NRs. The $\Delta T_{\text{phase}}$ of the bare VO$_2$ was 0, meaning that its $T_{\text{phase}}$ did not change at all under both polarizations. On the other hand, an increase of $\Delta T_{\text{phase}}$ was clearly observed as area densities of Au NRs increased as shown in Fig. 1.

Possible mechanisms are discussed. There are several possibilities attributable for plasmon-assisted VO$_2$ phase transition. Local heating effect of plasmonic nanostructure is one of the possibilities, which is caused by an internal decay of hot electrons inside a metal nanostructure, resulting in a significant heating of the nanostructure and its surrounding media through electron-electron and electron-phonon scattering relaxation processes. In addition, a direct injection of hot electrons into VO$_2$ accompanied with LSPR excitation is also undeniable as reported by Appavoo, et al.$^2$.

In summary, obvious decrease in $T_{\text{phase}}$ of VO$_2$ under LSPR excitation was observed compared to that measured under LSPR non-excitation at the same sample location, indicating the LSPR of Au NRs assisted VO$_2$ phase transition.

![Fig. 1 Differential phase transition temperature ($\Delta T_{\text{phase}}$) as a function of Au NRs area densities.](image)

References